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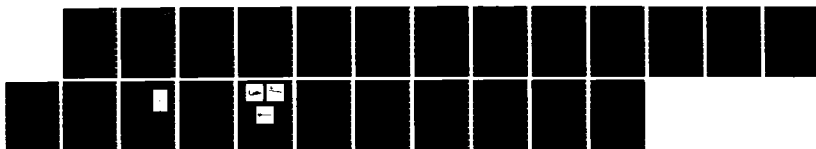
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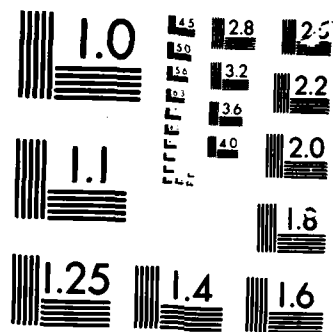
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Interaction of an Intense Relativistic Electron Beam with Preformed Channels

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<p>We report the interaction of an intense relativistic electron beam (REB) with preformed channels in gaseous atmospheres demonstrating the effects of reduced density, avalanche ionization, pre-existing conductivity, and channel currents. The intense REB for these experiments was produced from a field emission diode driven by the ≈ 1.4 MV pulse from a pulse forming line. Peak REB currents up to ≈ 16 kA, and current densities up to ≈ 2 kA/cm² were achieved. The time history of the REB was approximately a half-sinewave of width 27 ns (FWHM). Channels in the atmosphere were created using laser-guided electric discharges. Current-carrying reduced density channels were produced by applying a second discharge to the reduced density channel produced by the first discharge. Reduced density ($\leq \rho_0/80$), non-conducting channels were produced by the absorption of radiation from a pulsed CO₂ laser in ammonia gas at background pressures of ≈ 40 Torr ($\approx \rho_0/20$).</p> <p>Our results show that reduced density had little effect on REB propagation except for the decreased scattering, until it was reduced so much that the generation of conductivity changed. Avalanche ionization in a uniform atmosphere increased the growth of instabilities but when avalanche ionization was confined to a reduced density channel the REB</p> <p style="text-align: right;">(Continues)</p>				
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19. ABSTRACT (Continued)

was always repelled or expelled from the channel. Pre-existing conductivity in the form of a conducting channel with conductivity, $\sigma \geq 0.1$ S/m, also caused the REB to be repelled or expelled from the channel. However, the presence of a parallel channel current permitted the REB to be readily injected into the channel and guided along it with minimal losses. All of these effects and the thresholds at which they occurred are consistent with our present understanding of the interaction of intense REBs with gaseous atmospheres.

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INTERACTION OF AN INTENSE RELATIVISTIC ELECTRON BEAM WITH PREFORMED CHANNELS

I. INTRODUCTION

An intense relativistic electron beam (REB) propagating through the atmosphere leaves a "channel" that has a reduced density (after expansion) and continuing conductivity. Subsequent REB pulses or even later portions of a long pulse must interact with this channel and may be guided by it, may propagate more easily in it, or may be deflected by it. The concept of "hole boring" assumes that propagation in such a channel will increase the range of an intense REB in the atmosphere.^{1,2} And for Inertial Confinement Fusion (ICF) reactors it has been suggested^{3,4} that reduced-density current carrying channels, produced by laser guided electric discharges, will guide several light ion beams to the same target allowing significant increase in the power density at the target. Clearly, to assess the potential of charged-particle-beam directed energy weapons and of certain scenarios for ICF reactors, we must understand the interaction between an intense REB and a "channel" in the atmosphere. In this paper, we report the results of experiments which studied the interaction of an intense REB with preformed channels in gaseous atmospheres. These results demonstrate the effects of reduced density, avalanche ionization, pre-existing conductivity, and channel currents; and confirm our understanding of such phenomena.

In section II, we give a brief description of the physical processes occurring when an intense REB interacts with a gaseous atmosphere, while in section III, we describe the apparatus and the experimental procedure. The results of the experiments and a discussion of their interpretation are given in section IV.

II. REB/ATMOSPHERE INTERACTION

When an intense REB is launched into the atmosphere, a complex interaction occurs.⁵ A beam current, I_B , flows; the relativistic electrons cause direct collisional ionization proportional to the beam current density,

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J_B ; and avalanche ionization can occur if the air density is low enough and/or the rate of rise of beam current, dI_B/dt , is high enough. Subsequently, these plasma electrons recombine with their positive ions, or attach to oxygen (and other) molecules to form negative ions. Thus the growth of the electron density is governed by the interaction of four terms in the rate equation: direct collisional ionization, avalanche ionization, dissociative attachment and associative recombination;

$$\dot{n}_e = \frac{1}{c} \frac{d\epsilon}{dz} \frac{J_B}{e} + \alpha n_e - n n n_e - \beta n_e^2 \quad (1)$$

These four terms are implicit and/or explicit functions of the gas density, n , the electron density, n_e , and the electric field, E . The conductivity, σ , of a gas is a function of the electron density and the gas density,

$$\sigma = \sigma(n_e/n),$$

so that the conductivity in the channel can be represented as

$$\sigma = \sigma_{\text{initial}} + \int_{\text{time}} (\text{change due to REB}),$$

where σ_{initial} is the conductivity in the channel before the arrival of the REB. This conductivity, at first, neutralizes the strong radial electric field caused by the beam charge density, $n_e = n_b$, where n_b is the REB charge density; thus eliminating the radial electrostatic expansion of the REB. At somewhat higher values,

$$\sigma = c/(40\pi r_b), \quad (2)$$

where c is the velocity of light in vacuum and r_b is the radius of the REB, theory⁶ predicts that a weak (electrostatic dipole) attractive force will exist between the head of a REB pulse and a pre-existing channel. But at still higher conductivity, the REB induced electric field (proportional to dI_B/dt) causes a plasma current, I_p , to flow in the channel that is initially anti-parallel to I_B . Thus the magnetic field from this plasma current tends to push the REB out of the channel.

A subtle difference occurs between pre-existing high channel conductivity and high channel conductivity that is induced by the REB. In the latter case, the REB is first pushed out of the channel, but as it leaves the channel, the

plasma current in the channel reverses sign and begins to decay. At the same time, the REB begins to create conductivity along its new path. Thus the REB is soon being pushed away from its new path while it is attracted back to its old path. Such interaction between the REB and the plasma current is unstable⁷ and leads to disruption of the REB.

The decay of conductivity, after the passage of a REB pulse, is equally complex, depending not only on the chemistry of air but also on the dissipation of the energy stored in the magnetic field. Since, in the tail of a REB pulse, dI_B/dt is necessarily negative, the plasma current is now parallel to I_B and tends to stabilize and guide the REB. Similarly, if a pre-existing current, parallel to the REB current, could be superimposed on the channel, the REB should be "captured" in the channel and propagate stably.

We have conducted a series of experiments on REB propagation to investigate the different sources of conductivity in Eq. (1), the effect of pre-existing conductivity, and the effect of pre-existing channel current. With the available REBs, collisional ionization is always the dominant mechanism for conductivity production in the atmosphere. Furthermore, these REBs do not form well defined channels and multiple REB pulses, with suitable time separation, are not available. Thus to study the effects of avalanche ionization, we have propagated the REB in gases at reduced density, and to study the effects of pre-existing channels, we have created these channels independently. To effect pre-existing channel current, we have used current carrying reduced density channels, formed by laser guided electric discharges.

III. EXPERIMENTAL PROCEDURE

The intense REB for these experiments was produced from a field emission diode driven by the ≈ 1.4 MV pulse from a folded Blumlein pulse forming line (a modified Pulserad 310 generator, manufactured by Physics International Co., San Leandro, CA.) The cathode was a graphite annulus, 2.5 cm o.d., 1.2 cm i.d., with a semi-toroidal cross section. The anode was a titanium foil of thickness 0.038 mm. The REB emerging from the anode foil contained ≈ 16 kA within the foil diameter of 10.4 cm and ≈ 2.5 kA through a central aperture of diameter 1.5 cm. The time history of the REB was approximately a half-sinewave of width 27 ns (FWHM). In most of these experiments, the REB was injected into the laboratory atmosphere directly from the anode foil. In later experiments, the REB was allowed to propagate through a 50 cm long drift

tube before reaching a large experiment chamber or being emitted into the laboratory atmosphere. The drift tube was filled with ≈ 20 Torr of nitrogen and contained a conical return current conductor whose diameter reduced from ≈ 10.4 cm at the diode foil to ≈ 2.5 cm at the end of the drift tube. As it emerged from a second foil at the output end of the drift tube, the REB contained typically ≈ 10 kA within its diameter of ≈ 2.5 cm, and the duration of the pulse had been shortened to ≈ 21 ns (FWHM) because of erosion of the low energy "head" of the REB in the drift tube.⁸ When this REB was injected into the laboratory atmosphere, the typical net current peaked at ≈ 6 kA and was delayed with respect to the beam current (see Figure 1), showing that a substantial anti-parallel plasma current existed during most of the beam current profile. A similar result was obtained with the ≈ 16 kA REB, and both beams were "hose" unstable.⁷ The ≈ 2.5 kA REB produced very little plasma return current when injected into the atmosphere and propagated stably for ≈ 100 cm before Nordsieck expansion⁹ reduced its current density to an insignificant level.

Channels in the atmosphere were created using laser-guided electric discharges¹⁰⁻¹² (LGED) in which the beam from a Q-switched Nd:glass laser induced air breakdown off aerosols and these plasmas guided the electric discharge (≈ 250 kV, ≈ 1000 J, period ≈ 3 μ s, peak current ≈ 10 kA). At early times (≈ 100 μ s after initiation of the 250 kV discharge), the channel was highly conducting (conductivity, $\sigma \approx 44.0$ S/m), its radius was ≈ 1 cm, and the channel density was $\approx 0.05 \rho_0$, where ρ_0 is normal atmospheric density. Later the channel cooled becoming effectively non-conducting ($\sigma \ll c/40 \pi r_b$) at ≈ 500 μ s when the radius had grown to ≈ 1.5 cm and the density had risen to $\approx 0.2 \rho_0$. Current carrying reduced density channels were produced by applying a second discharge to the reduced density channel produced by the first discharge.¹³ As indicated in figure 2, techniques were developed to enable the creation of these channels immediately in front of the anode foil, thus permitting direct injection of the REB into the channel.

For channels in the sea-level atmosphere, avalanche ionization is not usually important, but at reduced ambient density, this is not always true.¹⁴ To explore this regime channels were produced in the large experiment chamber (a fiber-glass tank, 60 cm in diameter and 150 cm long) which was filled with ammonia to a pressure of 40 Torr. Reduced density channels were produced by the absorption of radiation from a pulsed CO₂ laser,^{15,16} with the laser beam

again directed towards the foil through which the REB was to emerge. Because ammonia dissociates¹⁷ rather than ionizes, these channels were non-conducting at least until the arrival of the REB. The density profile and the average conductivity of these channels in ammonia, prior to the arrival of the REB, were determined using double exposure holographic interferometry¹⁸ and an RF transmission line bridge,¹⁹ respectively. Typically the radius of the reduced density channel was ≈ 2.5 cm and the minimum density on axis was one-fourth the background density.

IV. RESULTS AND DISCUSSION

In the first experiments, the ≈ 2.5 kA REB was injected coaxially into channels in the atmosphere created by LGEDs. The resultant net currents are shown in Table 1.

Table 1. Net Current Measurements.

Channel	Peak Net Current
Unperturbed atmosphere	$2.4 \pm .05$ kA
Channel at 100 μ s	$2.1 \pm .09$ kA
Channel at 500 μ s	$2.4 \pm .05$ kA

When this REB was injected into the unperturbed atmosphere, the peak net current was almost equal to the peak beam current. This was also true when the REB was injected into the very weakly conducting channel that existed at 500 μ s, even though the density in the channel was $\approx 0.2 \rho_0$. When the REB was injected into the highly conducting channel that existed at 100 μ s, the peak net current fell below the peak beam current and was delayed from it. In this case, the REB was always ejected from the channel within a propagation distance of ≈ 10 cm even though without the channel the REB propagated as a straight beam for almost 100 cm. This ejection is consistent with the repulsion between the REB and the plasma return current, bearing in mind that the plasma electrons, that carry the return current, are fixed in position by the inertia of the positive ions.

Subsequently, photographs were taken of the interaction of the ≈ 2.5 kA REB with channels in the atmosphere; typical results are shown in figure 3. For coaxial injection into a highly conducting channel, figure 3a) shows that the REB was ejected and spread out around the channel most probably in an expanding helix. In this case, a Rogowski coil surrounding the channel recorded the plasma return current, showing the characteristic signal shape depicted in figure 1, and demonstrating that the plasma return current does indeed flow preferentially in the pre-existing conducting channel. When the REB was injected at an angle of $\approx 11^\circ$ to the channel and so as to intersect it (Figure 3b), the REB was "reflected" off the highly conducting channel. These deleterious effects of the highly conducting channel are consistent with the electromagnetic repulsion between the REB and the plasma return current, but theory⁶ also predicts that a weak attractive force exists between an REB and a channel with intermediate conductivity, Eq. (2). This level of conductivity (≈ 0.03 S/m) existed in the channel at approximately 350 μ s. Unfortunately, the electrostatic force is so weak that in these experiments it was masked by the effects of scattering off air molecules. However, we were able to demonstrate (Figure 3c) that at this conductivity the REB could be injected into the reduced density channel and would propagate along it without being ejected. Then the plasma return current was the same as in the unperturbed atmosphere, very small.

The REB/channel interaction was completely changed when there was a parallel current flowing in the channel.¹³ For these experiments, channel currents of 10 to 60 kA were superimposed on the highly conducting channel, and REBs of ≈ 16 kA or ≈ 2.5 kA were launched either coaxially or at an angle of $\approx 11^\circ$ into the channel. Because these channels were highly luminous, at the time the REB was interacting with the channel, the position of the REB was detected by the x-ray emission produced when the beam impinged on fine tungsten wires placed in the channel. This x-ray emission was monitored by both x-ray PIN diodes and an open shutter x-ray pinhole camera. Typical diode signals are shown in Table 2. For a constant voltage REB, these signals are directly proportional to the REB current. With no channel, neither REB gave a measurable signal at 100 cm even in the "straight ahead" direction: the ≈ 16 kA REB because of the large amplitude hose instability, and the ≈ 2.5 kA REB because of Nordsieck expansion. With a channel and parallel channel current, the ≈ 16 kA REB propagated mostly outside the reduced density channel and therefore suffered air scattering losses. The ≈ 2.5 kA REB propagated within

Table 2. REB Transport in Current Carrying Channels

CASE (1) I = 16 kA; Coaxial Injection B		
Position (z)	Channel Condition	Diode Signal
30 cm	60 kA	101±11
30 cm	No Channel	73±18
100 cm	60 kA	53±3
100 cm	No Channel	0

CASE (2) I = 16 kA; 11° Injection Angle B		
Position (z)	Channel Condition	Diode Signal
100 cm	60 kA	53±11
100 cm	36 kA	33±5
100 cm	No Channel	0

CASE (3) I = 2 kA; Coaxial Injection B		
Position (z)	Channel Condition	Diode Signal
30 cm	No Channel	12.5±2

CASE (4) I = 2 kA; 11° Injection Angle B		
Position (z)	Channel Condition	Diode Signal
30 cm	60 kA	12.5±3.5
30 cm	36 kA	12±1.4
100 cm	60 kA	10±1
100 cm	48 kA	10±1.4
100 cm	36 kA	13±1.4
100 cm	No Channel	0

the reduced density channel, showing no expansion and no measurable losses over the 105 cm channel length. Both REBs were "captured" by the channel, steered through the 11° angle, and transported over the 105 cm length of the channel with losses apparently due only to air scattering. This result is consistent with present theory which predicts that the magnetic field caused by a parallel channel current will stabilize and guide the REB. With anti-parallel channel current either REB was immediately expelled from the channel.

In normal atmospheric pressure air, the particle density is so high that the avalanche ionization coefficient is negligible and the dominant term in the rate equation (Eq. (1)) is that due to direct collisional ionization. However, the avalanche ionization coefficient,¹⁷ α , is a very strong function of the density normalized electric field, E/n . Thus the avalanche ionization coefficient increases if either the gas density drops, as in a channel, or the electric field increases. When the REB was injected into 40 Torr ammonia, it produced an initial normalized electric field of ≈ 200 Townsend (Td), slightly increasing the overall ionization rate. This same REB injected into a reduced density channel in an otherwise uniform background pressure of 40 Torr ammonia developed a higher density normalized electric field of ≈ 800 Td within the channel. The avalanche ionization rate then became so large that it was the dominant term in the electron production rate equation. Thus, when the ≈ 10 kA REB was injected into reduced density channels in ammonia at ambient pressures of 40 Torr, the REB was always ejected from the channel even though the channel conductivity was initially negligible ($< 10^{-7}$ S/m), because the electric fields generated by the REB as it was injected into the experiment chamber were sufficient to cause avalanche ionization in the reduced density channel but not in the background gas. The conductivity in the channel was therefore always much higher than that outside the channel, no matter whether the REB was in the channel or not. Once again, the plasma return current flowed preferentially in the channel and the REB was always ejected or repelled. At no time did the reduced density channels in ammonia attract or guide the REB.

This interpretation of the behavior of the REB in the presence of the reduced density channels was further verified by injecting the REB into the "channel" immediately (≈ 2 μ s) after absorption of the laser energy. At that time, the channel density was still ambient because the channel had not had time to expand appreciably but the channel temperature was elevated. (The radius of these reduced density channels was ≈ 1.2 cm or ≈ 2.5 cm). Then the presence of the hot channel had no effect on the propagation of the REB,

showing that reduced density not channel temperature was the underlying cause of the later time REB/channel interaction.

The behavior of the REB, in the presence of the reduced density channel in ammonia, must be compared to its behavior when injected into the ammonia with no reduced density channel, i.e. a uniform gas at 0.5 Torr or 40 Torr. We can describe the behavior of the REB in terms of a parameter, f^* , which is a measure of the peak plasma current. For $t < 20$ ns,

$$f^* = 1 - \frac{(I_N)_{\max}}{(I_B)_{\max}} \leq \left\{ \frac{|(I_p(t))|}{(I_B(t))} \right\}_{\max} \quad (3)$$

where I_B , I_p , and I_N are the beam, plasma, and net currents respectively. The observed behavior of the REB for different values of f^* is listed in Table 3. We note that values of f^* from ≈ 0.0 to ≈ 0.5 could be produced in either dry nitrogen or ammonia by changing the fill pressure and the inductance of the return current path provided outside the chamber.

Table 3. Effects of plasma current

f^*	Behavior
≈ 0.0	REB goes straight - slight kinking visible
≈ 0.3	Moderate hosing evident
≈ 0.5	Violent hosing evident
≈ 0.7	REB dispersed (in presence of channel)

A stability analysis²⁰ of a flat current profile REB injected into a collisional plasma showed a marked dependence for many transverse oscillations on the ratio of the plasma current to the beam current. The "hose" mode was absolutely growing whenever the plasma current was negative, but many other fast growing modes were triggered when the returning plasma current reached 50% of the REB current. It is difficult to make quantitative comparisons of instability growth with theory because theory is based on small amplitude linear approximations whereas all observations were of large amplitude perturbations of the REB. However, we did find throughout this study that whenever $f^* \geq 0.5$ the beam oscillations became particularly violent.

V. CONCLUSION

We have examined the interaction between an intense relativistic electron beam and preformed channels in air at normal atmospheric pressure and in ammonia at 40 Torr background pressure. Channels in air were created using the techniques of laser guided electric discharges in which a Nd:glass laser preionized a path through the air that subsequently was heated by the discharge from a 250 kV Marx generator. Current-carrying reduced density channels were created by applying a second discharge to the reduced density channel produced by the first discharge. Reduced density channels in ammonia were created by the absorption of energy from a CO₂ laser pulse. These channels in ammonia had very low initial conductivity ($<1 \times 10^{-7}$ S/m) and lasted for over 1 ms. The intense REB for these experiments was produced from a field emission diode driven by the ≈ 1.4 MV pulse from a pulse forming line. By using the REB as it emerged from the anode foil or after passage through a low pressure drift tube, three distinct REBs were produced: ≈ 16 kA within a diameter of ≈ 10 cm, ≈ 10 kA within a diameter of ≈ 2.5 cm, and ≈ 2.5 kA within a diameter of 1.5 cm.

Our results show that reduced density had little effect on REB propagation except for the decreased scattering, until it was reduced so much that the generation of conductivity changed. At high ambient pressures, i.e., near atmospheric pressure, and for modest REB characteristics, i.e., $\dot{I}_B \leq 10^{12}$ A/s, the conductivity in the reduced density channel was governed by the inherent conductivity of the hot plasma combined with the collisional ionization produced by the REB electrons themselves. At lower ambient pressures or larger values of dI_B/dt , avalanche ionization can contribute significantly to the channel conductivity. Avalanche ionization in a uniform atmosphere increased the growth of instabilities but when avalanche ionization was confined to a reduced density channel the REB was always repelled or expelled from the channel. Pre-existing conductivity in the form of a conducting channel with conductivity, $\sigma \geq 0.1$ S/m, also caused the REB to be repelled or expelled from the channel. However, the presence of a parallel channel current permitted the REB to be readily injected into the channel and guided along it with minimal losses. All of these effects and the thresholds at which they occurred are consistent with our present understanding of the interaction of intense REBs with gaseous atmospheres.

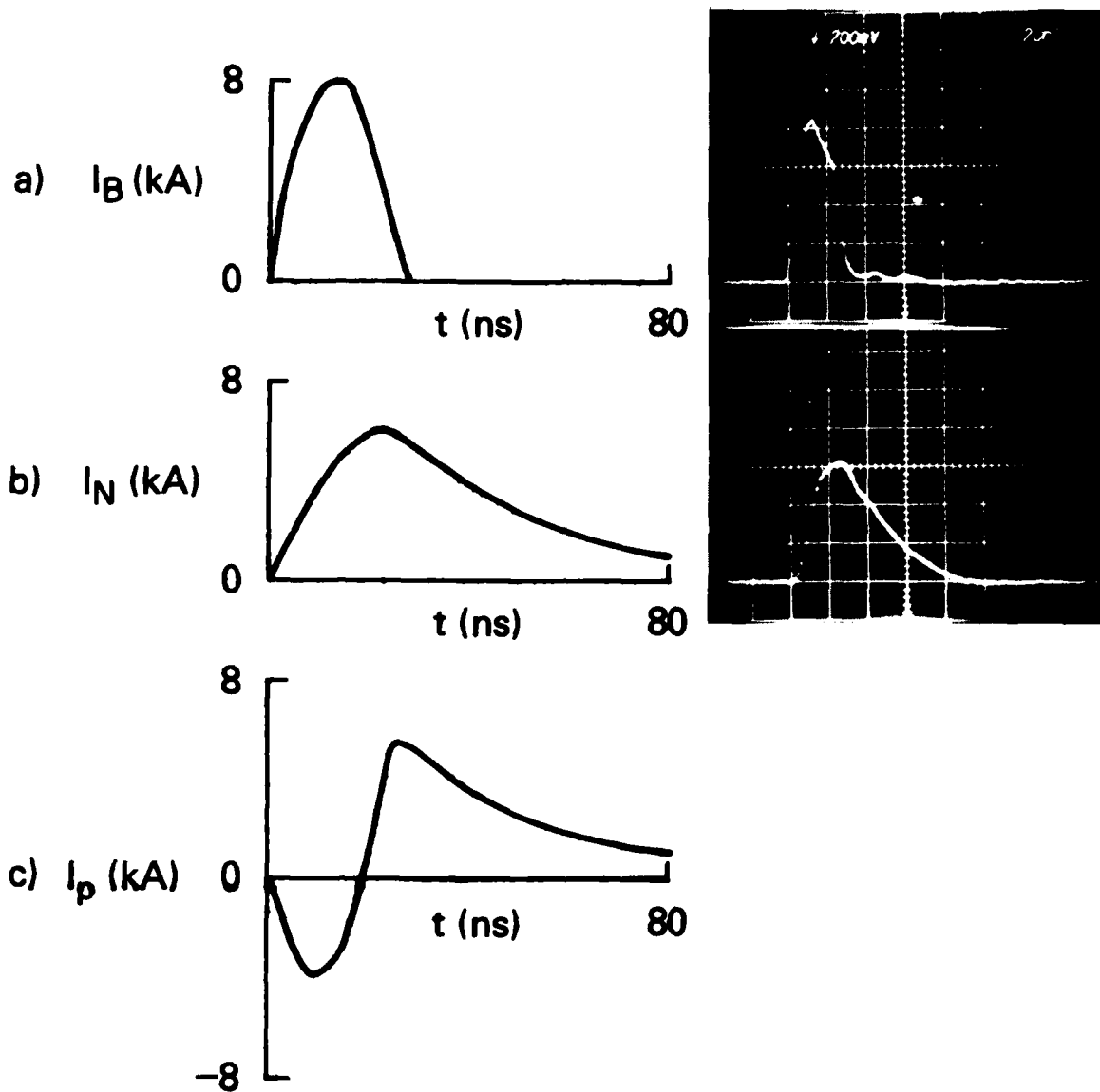


Figure 1. Single shot and average current measurements for an intense REB injected into the laboratory atmosphere: a) beam current and b) net current. The plasma current determined from $I_p(t) = I_N(t) - I_B(t)$, is shown in c).

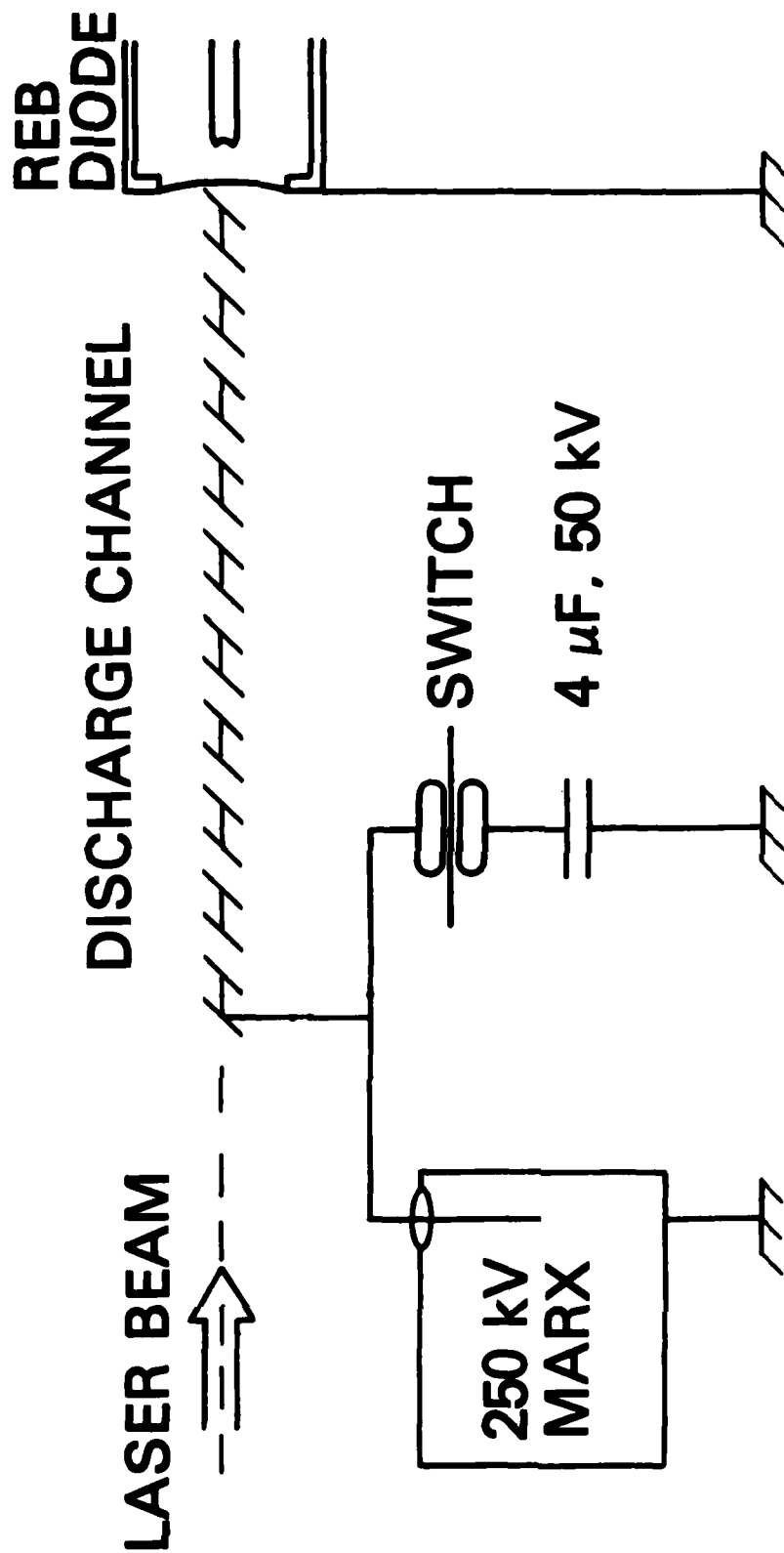
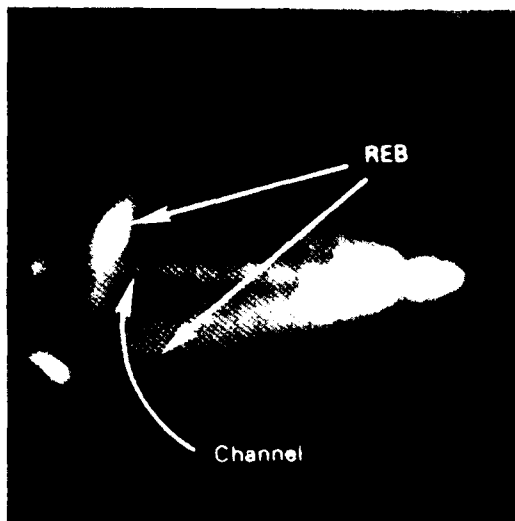
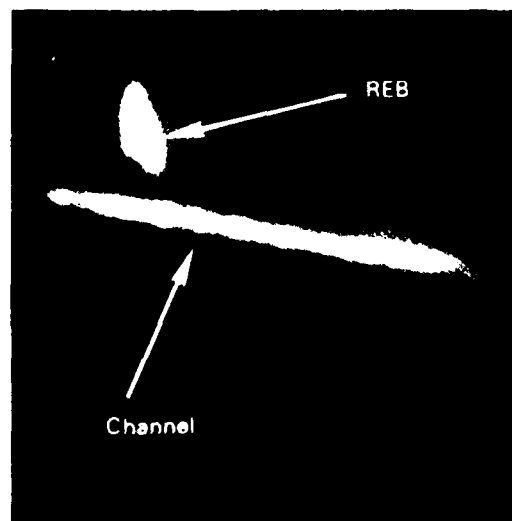


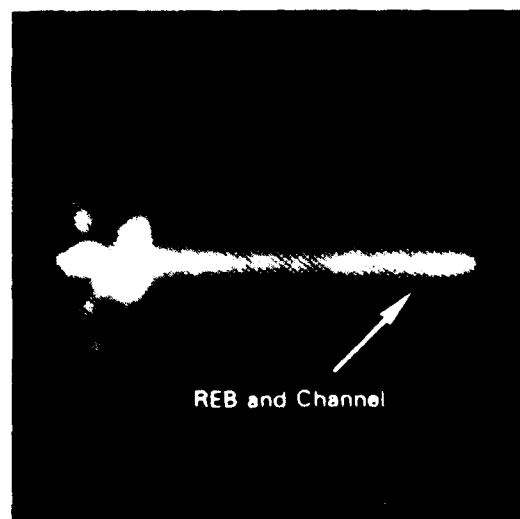
Figure 2. System for producing laser guided electric discharges in the atmosphere. Conducting reduced density channels are produced by firing the Nd:glass laser and the 250 kV Marx generator. A channel current can be superimposed on the reduced density channel by closing the switch after the reduced density channel has formed.



(a)



(b)



(c)

Figure 3. Photographs of the ≈ 4.5 kA REB interacting with channels in the atmosphere. a) Horizontal highly conducting channel (at ≈ 100 μ s), REB injected coaxially from right. b) Highly conducting channel (at ≈ 40 μ s) inclined at $\approx 11^\circ$, REB injected horizontally but with vertical offset. c) Horizontal channel with optimal conductivity (≈ 350 μ s) and density $\approx \rho_0/6$, REB injected coaxially from right. The horizontal length of the channel was 50 cm. Visible light with exposure time of 200 ns.

VI. ACKNOWLEDGMENT

The idea for REB/channel interaction studies in ammonia was suggested to us by Dr. R.B. Miller of Sandia National Laboratory, Albuquerque. We wish to thank our colleagues at NRL for many discussions that have helped develop our understanding of these experiments. We give special thanks to Dr. A.W. Ali for unravelling the intricacies of ammonia chemistry and to Dr. R. Fernsler. This work was supported by the Defense Advanced Research Projects Agency, monitored by the Naval Surface Weapons Center, and by the Office of Naval Research.

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